Time-reversal violation (*TRV*) in radiative β decay

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When designing *TRV* decay experiments:

- **What underlying physics generates the *TRV*?**
- **How big are the 'final state effects'?**
- **Is anyone else doing it better?**
- **How strong are the contraints from null EDM's?**

Our TRV observable needs 3 uncorrelated momenta:

$t \to -t \Rightarrow \vec{p} \propto \frac{d\vec{r}}{dt} \to -\vec{p}$

We routinely measure

$\vec{p}_\nu = -\vec{p}_\beta - \vec{p}_{recoil}$

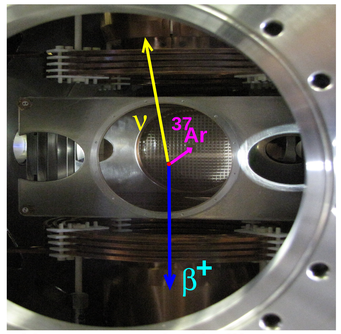
but $\vec{p}_{recoil} \cdot \vec{p}_\beta \times \vec{p}_\nu \equiv 0$ ☹

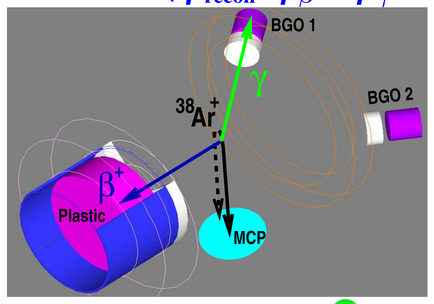
$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma =$

$-\vec{p}_{recoil} \cdot \vec{p}_\beta \times \vec{p}_\gamma$

$\xrightarrow{t \to -t}$

$+\vec{p}_{recoil} \cdot \vec{p}_\beta \times \vec{p}_\gamma$



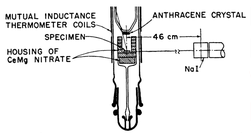


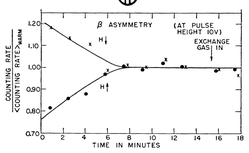
TRV makes $\neq \gamma$ rates ☺

Coincident pairs test detector symmetry ☺

- **Not exact: don't flip $\psi_i \leftrightarrow \psi_f$. Outgoing particles interact by *E&M* → 'final-state' *TRV* asym $\leq 10^{-3}$ for ^{37}K ☺ (Gardner,He 2013)**
- **Would be unique to 1st generation, complementary to $K^- \to \pi^0 e^- \bar{\nu}_e \gamma$ INR Moscow 2007, $A_{TRV} = -0.015 \pm 0.021$**

Parity broken, why not *T*ime?





Immediately after *P*arity was seen to be totally broken in β decay ('ν left-handed')

Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413

many T-odd observables were proposed:

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Possible Tests of Time Reversal Invariance in Beta Decay

J. D. JACKSON,* S. B. TREIMAN, AND H. W. WYLD, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received January 28, 1957)

Observables with spin $D\hat{J} \cdot \frac{\vec{p}_\beta}{E_\beta} \times \frac{\vec{p}_\nu}{E_\beta}$ $R\vec{\sigma}_\beta \cdot \hat{J} \times \frac{\vec{p}_\beta}{E_\beta}$ are consistent with *TRV* asymmetries < 0.001

Our observable could still be bigger ☺

QCD-like interactions generate antisymmetry

Harvey, Hill, Hill, PRL 2007; **Gardner, He PRD 2013:**

QCD ↓ Weak decay ↓ E&M ↓

$$\mathcal{L} = \frac{-4c_5}{m_{nucleon}^2} \frac{eG_F V_{ud}}{\sqrt{2}} \epsilon^{\sigma\mu\nu\rho} \bar{p}\gamma_\sigma n \bar{\psi}_{eL}\gamma_\mu \psi_{\nu L} F_{\nu\rho}$$

Interference with S.M. β decay 'vector current' makes the scalar triple product we seek ☺**:**

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{M^2} \frac{E_e}{p_e k} (\vec{p}_e \times \vec{k}_\gamma) \cdot \vec{p}_\nu$$

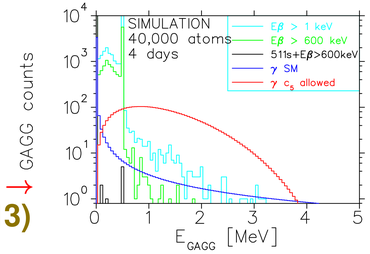
Needs QCD-like physics, scale *M* ~ 10's of MeV

- **This *TRV* scales with $p^2_{lepton} \to$ ~10^2 larger in ^{37}K decay than neutron**
- **Direct constraint from n → p $\beta\nu\gamma$ branch $\propto |c_5|^2$**

Bales PRL 2016: $3.4 \pm 0.2 \times 10^{-3}$ (theory 3.1×10^{-3})

$\Rightarrow \frac{Im(c_5)}{M^2} \leq 8 MeV^{-2} \Rightarrow$ **^{37}K *TRV* asym can be ~ 1** ☺

E_γ spectrum is distinctive ☺



- **Classical bremsstrahlung $\propto 1/E_\gamma$, but**
- **Any time-reversal violating interaction involves β, ν, γ ⇒ 4-body phase space $\propto E_\gamma(Q - E_\gamma)^3$** Bernard PLB 2004

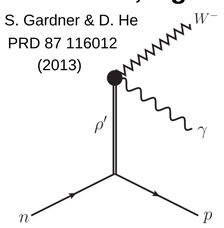
We are concentrating on $E_\gamma > 511$ keV, with the β^+ in the opposite detector

Constraint from neutron EDM on *TRV* $\beta\nu\gamma$

Though $\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma$ doesn't involve spin, EDM's indirectly constrain:

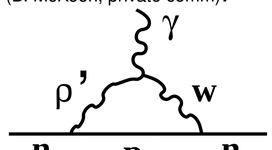
Some *TRV* $\gamma\beta\nu$ interactions, e.g. :

S. Gardner & D. He PRD 87 116012 (2013)



make neutron EDM at "1-loop" order

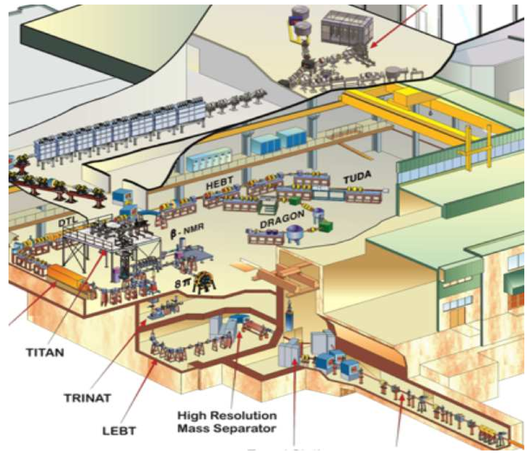
(D. McKeen, private comm):



"Naive Dimensional Analysis" $c_5 \frac{e^2 G_F M_W^3}{16\pi^2 m_{\rho'}^2}$ suggests nEDM larger than experiment by ~ 10^8.

→ *TRV* $\beta\nu\gamma$ from such interactions likely too tiny to measure ☹

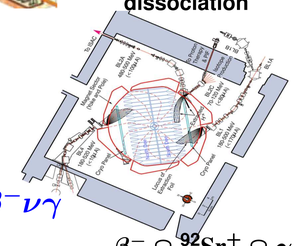
- **Other interactions (e.g. leptoquarks) need "2 loops" so generate comparatively tiny nEDM so are less constrained, could generate *TRV*$\beta\nu\gamma$ large enough to measure** ☺



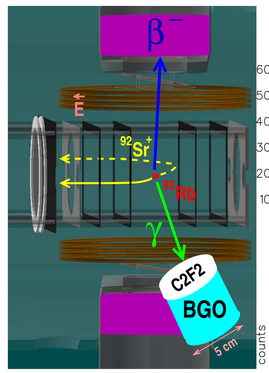
^{37}K 8x10^7/s TiC target 70 μA
1750°C protons
^{92}Rb 6x10^8/s UC_x target

TRIumf Neutral Atom Trap at ISAC

500 MeV TRIUMF cyclotron
H^-, 0.5 Tesla 'world's largest' orbits needed to avoid $\vec{E} = \vec{v} \times \vec{B}$ dissociation

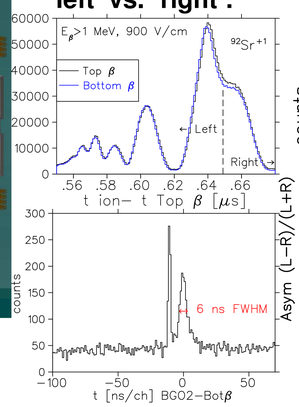


***TRV* test ^{92}Rb $0^- \to {}^{92}$Sr $0^+ + \beta^- \nu\gamma$**

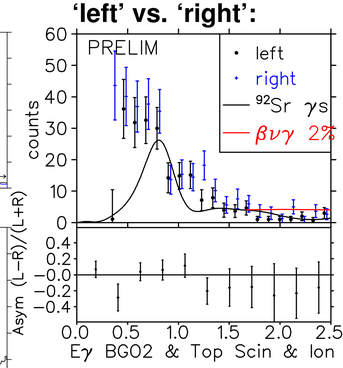


MOT + 'COLTRIMS'

$\beta^- \cap {}^{92}Sr^+$ **'left' vs. 'right':**



$\beta^- \cap {}^{92}Sr^+ \cap \gamma$ **'left' vs. 'right':**



Sensitivity to ≲ 2 % $\beta\nu\gamma$ branch

Asym of bkg is tricky

BGO → GAGG ($Ce:Gd_3Al_2Ga_3O_{12}$)

- **better E_γ resolution and timing, ρ= 6.6 g/cm^3**
- **Good photopeak efficiency • not radioactive like LYSO**

^{92}Rb decay: no vector current, constrains pseudoscalar TRV?

- **Plan: simple geometry has sensitivity to ~ 5-10% TRV asymmetry in ^{37}K or ^{38m}K**

That result could motivate a dedicated geometry